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Water budget and partial melting in an Archean crustal column: example from the Dharwar craton, India

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Abstract: The fluid budget of a composite crustal column is a critical parameter that influences many lithospheric processes. The amount of water introduced in the middle and lower crust can be quantified using phase equilibrium modelling. The Dharwar craton, India, displays a now-exposed continuous crustal section from near surface conditions to ~30 km depth. This section records the different steps of a ~15 Ma long high-temperature metamorphic event ($60\text{ }^{\circ}\text{C.kbar}^{-1}$), responsible for the formation of syn- to post-tectonic anatectic intrusions. The global water budget is assessed using thermodynamic modelling on bulk-rock compositions of an average early Proterozoic supracrustal unit (SU) and ca. 3.0 Ga felsic basement, the Peninsular Gneisses (B). Results show the fast burial of a water-saturated supracrustal package (1.6 wt.%) will release ~ 50 % of its mineral-bound water, triggering water-fluxed partial melting of the basement. Modelled anatectic magma compositions match the observed granitoid chemistries and distinction can be made between water-fluxed melting and water-absent melting in the origin of syn- to post-tectonic anatectic granites. Findings from this study show the importance of crustal pile heterogeneity in controlling the nature of partial melting reactions, the composition of the magmas and the rheology of the crust.

The amount of fluid circulating in the lithosphere (e.g. H_2O , CO_2) exerts a direct control on a large range of processes such as the nature of partial melting mechanisms (Stevens &

Clemens, 1993; Clemens, 2006; Weinberg & Hasalová, 2015; Nicoli & Dyck, 2018), magma crystallization in the crust (Waters, 1988; Nicoli et al., 2017), magma extraction and ascent (Holtz et al., 1994; Petford et al., 2000; Rosenberg & Handy, 2005; Sawyer et al., 2011), the style of volcanic eruptions (Gardner et al., 1995; Papale et al., 1998; Morizet et al., 2007), and to some extent, seismic activity along plates boundaries (Pili et al., 2011).

Quantifying the volume and flux of crustal water and fluid-mobile species through phase equilibrium modelling has been the focus of recent studies: In the oceanic lithosphere, this approach has been used to predict the behaviour of noble gases in subduction zones (Smye et al., 2017), the occurrence of blueschists mineral assemblages in convergent margins (Palin & White, 2016b) and even the fate of plate tectonics on other planets (Wade et al., 2017). By applying a similar approach to continental rocks metamorphosed under Barrovian conditions, Nicoli and Dyck (2018) showed that minor compositional variations that exist between Archean, Proterozoic, and Phanerozoic siliciclastic rocks can lead to significant variations in the depth and sequence of devolatilisation events, which *in fine* influence the nature of partial melting reactions and the chemistry of the resulting magmas. These variations are largely a response to the differences in bulk ferromagnesian and potassium content of the protolith. For Archean compositions, the high ferromagnesian content of the supracrustal lithologies increases chlorite stability at high temperatures and is responsible for greater than 60 vol.% of the water contained in H₂O-bearing mineral phases that can be released from the rock upon prograde metamorphism. Such a phenomenon will prevent or limit the formation of subsolidus muscovite and will lead to partial melting reactions dominated by fluid-absent biotite breakdown melting in the lower crust (Thompson, 1982; Clemens & Vielzeuf, 1987; Le Breton & Thompson, 1988; Vielzeuf et al., 1990; Stevens & Clemens, 1993; Patino Douce & Beard, 1996; Pickering & Johnson, 1998; Clemens et al., 2016). Importantly, regardless of the chosen geological area, the chemistry of the source exerts a primary control on the chemistry of the anatectic melt (Watt and Harley, 1993; Clemens and Stevens, 2012; Nicoli and Dyck, 2018). Parallel can be then drawn with the wide range of compositions observed in the anatectic intrusion population (Clemens and Stevens, 2012). However, the chemistry of the anatectic melt alone cannot account for the chemistry of crustal derived granite (e.g. Villaros et al., 2009; Nicoli et al., 2017). The chemistry of the resulting magma is best explained by the entrainment peritectic phases and accessory minerals (e.g. Stevens et al., 2007; Villaros et al., 2009; Garcia-Arias & Stevens, 2017) and disequilibrium mechanisms (e.g. Nicoli et al., 2017). Other mechanism such as fractional crystallisation and wall rock assimilation can also play a role in explaining magma chemistry (e.g. Clemens & Stevens,

2012). The reader is referred to Garcia-Arias & Stevens (2017) for the most recent review on mechanisms that controlled magma chemistry.

The extraction of water from metasedimentary units along the prograde path may be enhanced by deformation-propagated fluid flow (Connolly, 1997) and trigger reworking of the surrounding lithologies via water-fluxed melting (Weinberg & Hasalová, 2015), as evidenced in many tonalitic–*trondjemitic* terrains (e.g. Mogk, 1992; Nédélec et al., 1993; Lee & Cho, 2013). Although these mechanisms are well known, it is difficult to quantify fluid flux through the continental crust. It is crucial, however, to fill this gap in our knowledge as this phenomenon has direct implications on our understanding of the reworking and stabilization of the continental crust at the Archean-Proterozoic boundary (Nicoli et al., 2016 and references therein).

In this contribution, I show that phase equilibria modelling, can be used to (i) estimate the amount of water recycled in the crust in a given geological setting, (ii) distinguish between fluid-fluxed melting and mica breakdown fluid-absent melting in the origin of syn- to post-tectonic anatectic granites, (iii) estimate local changes in the rheology of the crust. For the purpose of this study, I use the well-constrained example of the Dharwar craton, India (Fig. 1a), where an entire 500 km long Meso- to Neoarchean crustal section is exposed, from sub-surface lithologies to lower-crust migmatites.

Geological setting

The Dharwar craton is a pristine Archean crustal cross-section, that was tilted to near horizontal during the *ca.* 1.0 Ga uplift of the Eastern Ghats Mobile Belt (Chadwick et al., 2000; Bhadra et al., 2004). The craton is divided into two crustal blocks - Western Dharwar craton (WDC) and the Eastern Dharwar craton (EDC), separated by the Chitradurga shear zone (Fig. 1a). The WDC and EDC differ in the degree of supracrustal exposure and volume of syn- to post-tectonic granitoid intrusions. In both blocks, the crustal cross-section from north to south is characterised by metamorphic conditions progressively evolving from greenschist facies conditions in the North, to granulite facies conditions in the South (Swami Nath et al., 1976; Rollinson et al., 1981) (Fig. 1b). South of the amphibolite-granulite boundary, the Peninsular gneiss are characterised by the presence of charnockites (Janardhan et al., 1982; Hansen et al., 1984; Raase et al., 1986; Drury et al., 1984; Gopalakrishna et al., 1986; Stähle et al., 1987; Naha et al., 1993; Bouhallier, 1995). Previous P-T estimates for both the high-grade orthogneiss and charnockite used (abbreviations after Kretz, 1983): Opx + Qtz + Grt + Cpx thermobarometers (Perkins & Newton, 1981) and Grt-Bt and Crd-Grt-Sill-Qtz barometers calibrated on metasedimentary rocks (Holdaway & Lee, 1977; Ferry & Spear,

1978). Compilation of metamorphic estimates on metasedimentary rocks, metamafic lithologies and basement units in the WDC indicate a prograde evolution along an average apparent geothermal gradient of $\sim 60\text{ }^{\circ}\text{C.kbar}^{-1}$, from $450\text{ }^{\circ}\text{C}$ and 2.5 kbar, in the north, to $900\text{ }^{\circ}\text{C}$ and 10 kbar, in the south (Fig. 1b).

In the EDC, U-Pb zircon ages indicate the TTG and granitoids emplaced at *ca.* 2.54 Ga underwent a partial melting event at granulite facies conditions between 2.52 Ga and 2.51 Ga (Friend & Nutman, 1992; Peucat et al., 2013). This regional tectometamorphic event is accompanied by juvenile magmatism and granitoid emplacement (e.g., Closepet granite, Bt-bearing granite, and TTGs). South of the Closepet granite, U-Pb monazite ages in charnockite gneisses give an age of *ca.* 2.51 Ga (Mahabaleshwar et al., 1995).

In the WDC, near Chittradurga (Fig. 1a), rocks are equilibrated under greenschist facies conditions. The minimum depositional age of the supracrustal lithologies in the Chittradurga schist belt have been dated at *ca.* 2.68 Ga (Hokada et al., 2013).

U-Pb analyses of zircon gave a metamorphic age of *ca.* 2.53 Ga (Peucat et al., 2013). Using Sm-Nd analyses of garnet and bulk rock compositions, Bouhallier (1995) dated prograde metamorphism at $2527 \pm 34\text{ Ma}$. At the amphibolite-granulite transition zone, the Neoarchean basement (2.6–3.0 Ga) underwent a regional metamorphic event at *ca.* 2.5 Ga (Peucat et al., 2013). In the granulite zone, the basement consists of magmatic and supracrustal rocks formed between 2.56 Ga and 2.7 Ga (Peucat et al., 2013) and the granulite facies metamorphic overprint has been dated at $2518 \pm 10\text{ Ma}$. Syn- to post-tectonic plutons intruded both the Peninsular gneisses and the Chittradurga Schist Belt (Taylor et al., 1984). To summarize, the now-exposed crustal section records the different steps of a $\sim 15\text{ Ma}$ long high-temperature metamorphic event ($60\text{ }^{\circ}\text{C.kbar}^{-1}$), contemporaneous with the formation a large volume of magmatic intrusions (Moyen et al., 2003).

The information listed above, combined with structural data (Bouhallier et al., 1995; Chardon et al., 1996; 1998), can be used to reconstruct the geodynamic evolution of the Dharwar craton (Fig. 2; Chadwick et al., 2000, 2007; Jayananda et al., 2006; 2018; Chardon et al., 2009). Between 2.6 Ga and 2.8 Ga, while the Chittradurga supracrustal unit formed on the stable basement (*ca.* 3.0 Ga TTGs and Sargur supergroup) in the WDC, the EDC experienced juvenile magmatism (i.e., TTGs and sanukitoids) and volcanism in back-arc settings. At *ca.* 2.5 Ga, the west-trending shortening event culminated with the accretion of magmatic arcs along the edge of the WDC. The closure of arc domains was followed by an intense reworking of the craton. In the WDC, differing density between the basement and the overlying supracrustal unit triggered the progressive vertical sinking of sedimentary and

volcanic lithologies towards lower-crustal levels, resulting in a dome and keel structural pattern. Similar mechanisms are thought to have happened in the EDC, however this part of the craton better displays the large range of anatectic granites formed during the event. The mantle underneath the Chitradurga shear zone re-melted and formed the Closepet granite and a range of mixed mantle and crustal derived syn- to post-tectonic granitoids.

Given its full and continuous exposure, and extensive above-described analyses, the Dharwar craton is an ideal natural laboratory to test the hypothesis of water-fluxed melting and quantify reworking processes in the crustal column.

Starting material

Compositions used as starting material for the phase equilibrium modelling come from the Condie's (1993) restoration model for the upper crust and average Peninsular gneiss composition. To determine composition of the supracrustal unit (SU), I used the average early Proterozoic supracrustal lithology compositions from Condie (1993) in the following proportions: 27.5% felsic volcanic, 25% basalt, 12.5% andesite, 35% greywacke (Condie, 1993) (Table 1). The resulting average supracrustal unit composition is characterised by a Mg# value of 0.28 and an A/CNK ratio of 1.29 (molar ratios: $Mg\# = Mg / ([Fe + Mg])$; $A/CNK = Al / [Ca + Na + K]$). The basement composition (B) was determined by directly averaging *ca.* 3.0 Ga Peninsular gneiss and potassium-rich intrusions compositions (70% and 30% respectively, Condie, 1993) which did not experience the *ca.* 2.5 regional metamorphic event (Taylor et al., 1984). Both lithologies display similar compositions (Mg#: 0.11-0.13; A/CNK: 1.11-1.17) (Table 1) and will undergo similar dehydration sequences during the prograde path.

Model setup

Phase equilibria of greywacke, basalt, andesite and felsic volcanics and the basement were modelled using version 6.7.5 of the Perple_X software package (Connolly, 2009) in the system $Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-O_2$ (NCKFMASHTO).

Calculations were done using the Holland & Powell (2011) thermodynamic database (<http://www.perplex.ethz.ch/>). Different a-x models were used for different lithologies.

Models used for greywacke, felsic volcanics and the basement were as follows: silicate melt, garnet, white mica, biotite, orthopyroxene, cordierite, chlorite (melt(G), Gt(W), Mica(W), Bi(W), Crd(W), Chl(W) - White et al., 2014); ilmenite-hematite (Ilm(WPH) - White et al., 2000); epidote (Ep(HP11) - Holland & Powell, 2011); plagioclase and orthoclase (Pl(I1,HP), Fsp(C1) - Holland and Powell, 2003).

Models used for basalt and andesite were as followed (after Palin et al., 2016b):

clinopyroxene, amphibole, melt silicate (Green et al., 2016); garnet, orthopyroxene, biotite, chlorite, muscovite-paragonite (Gt(W), Opx(W), Bi(W), Chl(W), Mica(W) - White et al., 2014); epidote (Ep(HP11) - Holland & Powell, 2011); plagioclase and orthoclase (Pl(I1,HP), Fsp(C1) - Holland and Powell, 2003); ilmenite-hematite (Ilm(WPH) - White et al., 2000).

Maximum water retention of the supracrustal unit can be obtained by first considering H₂O as a fluid phase in excess and then recalculating bulk H₂O by summing the water content in the different hydrous phases (Bt, Ms, Chl, Ep, Amph) (Nicoli & Dyck, 2018). Modal proportions of H₂O-bearing minerals were investigated along the geotherm - set at 60 °C.kbar⁻¹ - from 450 to 900 °C (Fig. 1b). At suprasolidus conditions, bulk H₂O content was fixed to be saturated at the point at which the geotherm intersects the solidus.

Results

Subsolidus water content

Major devolatilisation events within the supracrustal rock package mainly occurs during epidote and chlorite breakdown between 500 °C and 600 °C, depending of the composition of the source material (Fig. 3a-d). For mafic and intermediate rock compositions, biotite and amphibolite are stable above 450 °C and 520 °C respectively, and epidote and chlorite are exhausted between 530 °C and 560 °C (Fig. 3a,b). For the felsic volcanic composition (Fig. 3c,d), biotite is stable at T > 400 °C, epidote is exhausted at 550-600 °C. The greywacke composition (Fig. 3d) also experienced devolatilisation at 600 °C through chlorite and muscovite breakdown. The amount of mineral-bound water lost by the felsic volcanic, the andesite, the greywacke and the basalt is 0.34 wt.%, 0.75 wt.%, 0.81 wt.% and 1.48 wt.% respectively (Fig. 4a). The volume of mineral-bound water held in the supracrustal unit along the 60 °C.kbar⁻¹ geotherm varies from 1.6 wt.% at 450 °C to 0.8 wt.% at hydrated solidus conditions, ~ 690 °C, meaning major devolatilisation occurs with the loss of ~ 50 vol. % of the mineral-bound water (Fig. 3e, 4a).

In the basement, the volume of mineral-bound water varies from 0.42 wt.% at 450 °C to 0.22 wt.% at hydrated solidus conditions, ~ 690 °C (Fig. 3f). This means that ~ 50 vol% of water is lost from the system during devolatilisation, most of it happening between 450–510 °C with the progressive breakdown of epidote and muscovite (Fig. 3f). However, compared to the supracrustal unit, the volume of mineral-bound water in the basement remains constant above 510 °C. Based on the estimated rock volume proportions from stratigraphic columns and geological maps, Condie (1993) suggested that the volumetric ratio of the supracrustal unit over the basement (i.e. SU/B) for the early Proterozoic is 1.5. For a crustal column

corresponding to this ratio, the budget of buried mineral-bound water reaches a maximum of 1.24 wt.% (Fig. 4b). Such quantity might potentially trigger the partial melting of the surrounding basement in water-present conditions. On the other hand, partial melting of the basement under water-saturated solidus conditions can be achieved for a volume of mineral-bound water of 0.22 wt%, which would correspond to a SU/B ratio of 0.27 (Fig. 4b).

Anatectic melts

The solidus temperatures for biotite breakdown water-absent partial melting and water-fluxed partial melting are 745 °C and 690 °C respectively (Fig. 5a). The fertility of the basement (i.e. amount of melt produced) is a direct function of the amount of water available in the system. Water-fluxed melting will produce up to 24 vol.% of melt at peak metamorphic conditions (900 °C, 10 kbar), compared to ~ 4 vol.% in water-absent melting conditions (Fig. 5a). The volume of melt produced during water-fluxed melting is above the maximum 7 vol.% melt connectivity threshold (Rosenberg & Handy, 2005), while in absence of an excess of water, the system remains below this threshold. However, under stress, it is also likely this threshold can be reached for lesser melt content (Brown, 2013). Biotite breakdown starts at 745 °C, which corresponds with the onset of peritectic garnet (Fig. 5a). During biotite breakdown water-absent partial melting, peritectic orthopyroxene is also produced after exhaustion of biotite above 870 °C (Fig. 5a). Along the prograde path, water-fluxed partial melting first produces melts characterised by a lack of FeO and MgO (Fig. 5b). Overall, biotite breakdown water-absent partial melting and water-fluxed melting produce, within error, melts of similar composition. The main difference between the two partial melting scenarios therefore comes from the nature and abundance of magmatic and peritectic phases, e.g. feldspar, garnet, orthopyroxene and ilmenite/rutile.

Discussion

Rapid burial of a foreland basin system

The Dharwar craton displays a continuous crustal cross section from near surface conditions in the north to granulite facies metamorphism (30 km depth – average crustal density 2.8 kg.m⁻³ - Taylor & McLennan, 1995) in the south. In the northern part of the craton, gold-bearing schist belts have been interpreted to have formed in foreland continental margin environments between 2.6 Ga and 3.0 Ga (Chadwick et al., 2000). The preserved supracrustal material and associated basement in these schist belts (i.e. sedimentary derivative of the greenstone belts), such as the Chitradurga Schist Belt, have been interpreted as potential protoliths of the high-grade rocks observed in the South (Piper et al., 2003). The Chitradurga schist belt is composed of greywackes, phyllite, conglomerate, quartzite and volcanics (Naqvi

et al., 1972, 1988). The maximum deposition age is ca. 2.68 Ga (Hokada et al., 2013), followed by a crustal-shortening related deformation event at ca. 2.60 Ga (Chadwick et al., 2000) and a late regional low grade metamorphic episode at ca. 2.53 Ga (Peucat et al., 2013). The composition of the supracrustal unit used in this study falls into the spectrum of the lithologies observed in the Chitradurga Schist Belt (Naqvi et al., 1972).

Considering the basement and the supracrustal materials exposed in the northern part of the craton are equivalent in ages to the protoliths of the granulite facies rocks in the South (Piper et al., 2003), a minimum burial rate can be deduced by combining metamorphic information and age estimates. With a total duration of the prograde metamorphism of ~ 15 Ma and a maximum depth of ~ 30 km, the minimum burial rate is 1.9 km.Ma⁻¹. This is within the range of Archean orogenic burial rates (0.3–3.1 km.Ma⁻¹) (Nicoli et al., 2016). The estimated rates are similar to the ones found in the Barberton Greenstone Belt (1.7 ± 1 at 3.2 and 3.4 Ga) and the Eastern Ghast Mobile belt (1.4 ± 1 km.Ma⁻¹ at 3.0 Ga). Gravitational instabilities and sagduction mechanisms have been suggested for the rapid accumulation and burial of the supracrustal unit down to lower-crustal depths (Bouhallier et al., 1993; Collins et al., 1997; Chadwick et al. 2000; Jayananda et al., 2006; Chardon et al., 2009). Gravitational instabilities can be caused by the rapid accumulation of dense metasedimentary and metamafic material onto the basement. Density ratio $\Delta\rho_1$ ($\Delta\rho_1 = \rho_{\text{Supracrustal Unit}}/\rho_{\text{Basement}}$) between the supracrustal unit and the basement (Fig. 6), shows important increases in $\Delta\rho_1$ values along the prograde path at 550 and 600 °C, which corresponds to the exhaustion of chlorite and epidote in supracrustal rocks. Thus, the rapid accumulation of a 16–20 km thick, denser greenstone sequence (worldwide average thickness for greenstone belts: 16 ± 5 km - Condie, 1981) on a relatively thin crustal basement of 15–22 km (Pichamuthu et al., 1981) might have triggered or enhanced vertical instabilities. Additionally, the late Archean/early Proterozoic is characterised by a general high geothermal gradient (30–40 °C.km⁻¹), high topography and long-lasting shear zones (Chardon et al., 2009; 2011). Therefore, minor lateral crustal shortening events (Bouhallier et al., 1993) and an abnormal geotherm, combined with the fast development of large foreland basins filled with the weathered products of the surrounding mountains belts (80% sediments and 20% volcanics; Naqvi et al., 1988; Collins et al., 2007; Chadwick et al., 2000), might have explained the rapid accumulation of greenstone material and its fast subsequent burial.

Devolatilisation and water redistribution

Nicoli & Dyck (2018) showed that in addition of being an important water reservoir, Archean shales and greywackes buried along Barrovian P-T paths might release more than 60 vol. %

of their mineral bound water. In the case of the Dharwar craton, the supracrustal package might lose up to 50 vol.% of its mineral-bound water during the prograde path. The structural patterns (Bouhallier et al., 1995; Chardon et al., 1996, 1998) demonstrate a high degree of deformation and tectonic reworking, with slivers of supracrustal unit folded into the basement units. Such intense tectonic activity might have facilitated the burial of hydrous material while maintaining permeability channels in shear zones and fault systems, enhancing local fluid-fluxed melting (Etheridge et al. 1983; Connolly, 1997; Ward et al., 2008; Reichardt & Wienberg, 2012). As discussed in Nicoli & Dyck (2018), the potential dehydration of metasedimentary rocks during burial might favourite to the formation of gold-bearing quartz veins in Archean and Proterozoic metamorphic greenstone belts (Phillips & Powell, 1993; Robert et al., 1995; Jia & Kerrich, 2000; Phillips & Powell, 2010).

With the exception of the Hutti-Maski and the Hira-Buddinin greenstone belts in the Northern EDC, gold mineralisation occurs between ca. 2.51 Ga and ca. 2.53. It then overlaps with the lifespan of the metamorphic event and the generation of syn- to post-tectonics intrusions, including the Closepet batholith (Fig. 7; Chardon et al. 2002; Sarma et al., 2008; 2011; 2012; Bhattacharya et al., 2014). Fluids in the Hutti-Maski and the Hira-Buddinin greenstone belts has been interpreted to result from the devolatilisation and decarbonation of garnet and biotite-bearing amphibolite schist during an early subduction-related compressional tectonic episode at ca. 2.6 Ga, inferred to take place before the ca. 2.53 Ga regional metamorphic event. In the rest of the greenstone belts (i.e., Gadag, Ramagiri-Penakacherla, Ajjianahalli and Kolar; Fig. 7), the average age for the gold mineralisation decreases towards the South, possibly correlating with the progressive devolatilisation of the supracrustal rock packages during burial, i.e., epidote and chlorite breakdown. Thus, water-fluxed melting of the basement presented in this study represents an endmember scenario during which all of the mineral-bound water can be brought to lower-crustal level. In reality, it is likely that some of this water will ascent towards upper crustal levels, triggering the formation of syn- to post-tectonic mineralisation deposits.

Consequences of water-fluxed melting on the rheology of the basement

Weinberg and Hasalová (2015) argued that in some orogenic belts (e.g., Himalayas, southern Canadian Cordillera), the presence of water flux melting might be responsible for the weakening of the core of the orogen, leading to local extensional events. At smaller scale, similar mechanisms could have occurred in the Dharwar craton, triggering local rheological weakening. The density contrast $\Delta\rho_2$ ($\Delta\rho_2 = \rho_{\text{Basement water-absent}}/\rho_{\text{Basement water-fluxed}}$), between rocks that experienced water-fluxed melting and dryer parts of the felsic crust, is > 1 above

the solidus conditions and increases during decompression (Fig. 8). This supports the idea of local crustal weakening near the supracrustal rock keel/felsic dome contact zone. Such density contrast might have aided the development of magmatic channels, facilitating the rise of felsic magmas via small diapirs. Thus the observed dome and keel pattern (Bouhallier et al., 1995; Chardon et al., 1996; 1998) lends support to the idea that water-fluxed melting might have, to some degree, helped in affecting the regional-scale structure.

Syn- to post-tectonic anatectic granites

There is significant diversity of syn- to post-tectonic intrusions in the Dhawar craton (Moyen et al., 2001, 2003; Jayananda et al. 2000, 2006, 2018 and reference therein). In the Closepet batholith, the most voluminous intrusive phases are porphyritic granite and granodiorite, followed by anatectic granites (10-20 %) and clinopyroxene-rich monzogranite (~ 1%). Most of chemistry of the Closepet batholith is better explained by magma mixing between 50 % anatectic melt and 50 % mantle-derived magma (Moyen et al., 2001). Here, I only discuss anatectic component of the Closepet granite and other biotite-bearing intrusions scattered in the EDC and WDC. These intrusions are the result of the reworking of the basement, producing crustal-derived magmas, which later form intrusions at middle to upper crustal level (Jayananda et al., 2018).

Anatectic granite chemistry is achieved by mixing the anatectic melt with a fraction of mineral solid phases (Stevens et al., 2007; Garcia-Arias & Stevens, 2017; Nicoli et al., 2017). If the modelled melt compositions for the water-fluxed melting and the biotite breakdown water-absent partial melting scenarios partially reproduce the composition of the anatectic granites (Fig. 9), additional entrainment of peritectic and magmatic plagioclase is needed to reproduce the trends towards low $\text{Ca}/(\text{Ca}+\text{Na})$ and A/NK ratios. The presence of peritectic garnet and orthopyroxene also drives the magma composition towards higher $\text{Fe} + \text{Mg}$ content. The product of partial melting (melt + solid mineral phases), predicted by thermodynamic models, can be compared to syn- to post-tectonics anatectic granite compositions (Janardhan et al. 1982; Peucat et al., 1993; Jayananda et al. 2000; 2006; 2018; Moyen et al., 2001; 2003) to determine the pressure and temperature at which the magma started to form (Fig. 10). The modelled magma compositions have been obtained by considering the melt phase in addition to a maximum of 10 vol.% of peritectic phases and magmatic phases present above solidus (i.e., Grt, Opx, Ilm, Fsp) (Stevens et al. 2007; Nicoli et al., 2017). Na/K and $\text{Ca}/(\text{Fe}+\text{Mg})$ molar ratios have been used to reflect variations in the amount of these solid mineral phases in equilibrium with the anatectic melt. To avoid local minima, P-T estimates have been obtained by averaging the results of best fits for Na/K

molar ratios with best fits for Ca/(Fe+Mg) molar ratios. However, due to the choice of starting material (i.e. average gneiss composition) rigorous mineralogical assemblages, specific to a given sample, cannot be accurately reproduced (see next paragraph), which explains the significant errors on the P-T estimates.

For the biotite breakdown water-absent melting scenario (Fig. 10a), in the EDC and WDC, the majority of the intrusions form at ~ 825 °C and at 5-7 kbars. Intrusions from the EDC seem to preserve similar temperature and pressure conditions, 5-7 kbar.

The preserved P-T conditions change when an excess of water is introduced in the system (Fig. 10b). In both the WDC and the EDC, preserved temperatures range between 700 °C and 875 °C, close to wet-solidus conditions. The pressure estimates range between 2 and 13 kbars. While, some anatectic granites display peak pressures similar to the biotite breakdown water-absent melting scenario, 5–6 kbars, there are also some intrusions recording higher pressure conditions between 10 and 12 kbars.

The granite produced via biotite breakdown water-absent partial melting form at conditions at which the volume of melt < 10 vol.% (Fig. 10a), whereas granite derived from water-fluxed partial melting are characterised by melt volumes of 15-30 vol.% (Fig. 10b). In the Dharwar craton, the area occupied by anatectic granites in map represents 6-20 % of the exposed Precambrian crust (Chardon et al., 2008; Jayananda et al., 2018). If we consider melt volume estimates as proxies for produced magma volumes, water-absent melting of the basement cannot alone account for the amount of anatectic granite cropping out in the Dharwar craton.

Therefore, in the case of the Dharwar craton, anatectic granites produced from both biotite breakdown water-absent partial melting water-fluxed partial melting are likely to form at upper crustal levels. Similar conditions have been reported for the formation of syn-doming granitoids of the Mt Edgar Batholith, Pilbara, 750–775 °C and 4–6 kbar, during water flux-melting (Collins, 1993). However, intrusions resulting from the influx of water into the basement also crystallise near peak metamorphic conditions (> 10 kbars), arguing for a fraction of the magma being trapped at lower-crustal levels. This is consistent with less mobile magmas produced within an H₂O-saturated environment (e.g. Maaløe and Wyllie, 1975; Clemens and Vielzeuf, 1987). These scenarios, using either a restricted or excess water, demonstrate the full range of possible conditions at which anatectic magma can crystallise in the crust. It is likely that redistribution of water within the felsic basement will not be homogenous, resulting in different type of metamorphic reactions and anatectic magma compositions.

Limit of the modelling

This study demonstrates the usefulness of using thermodynamic modelling in constraining the influence of water on the crustal differentiation and the behaviour of magmatic systems. However, as for metamorphic systems, such an approach has some limitations. The work presented in this paper does not pretend to reproduce accurately the chemistry of the observed syn- to post-tectonic anatectic intrusions cropping out in the Dharwar craton. Rather, it highlights chemical trends and patterns that need to be interpreted with the frame of the entire crustal column. For a more accurate match, additional processes such as effective bulk compositions (e.g. Guevara & Caddick, 2016; Palin et al., 2016a), open system (Yakymchuk & Brown, 2014) and disequilibrium mechanisms (e.g. Taylor et al., 2014; Garcia-Arias & Stevens, 2017; Nicoli et al., 2017) would need to be considered.

Melting conditions may also have been influenced by the presence of other fluid phases such as CO₂, CH₄ and N₂. At mid- to lower-crustal levels, mixed CO₂-H₂O fluid flux decreases the solidus temperature (Percival, 1991) and stabilizes pyroxene phases. Increased CO₂ content lowers $a_{\text{H}_2\text{O}}$ at depth, which triggers the destabilization of biotite and amphibole (Janardhan et al., 1982). Possible evidence for a metamorphic CO₂ flux is found in the charnockised granites (Frost & Frost, 1987), which often contain fluid inclusions saturated in carbon dioxide (i.e., 70 - 100%) (Hansen et al, 1987; 1984; Touret et al., 2010). In the Dharwar craton, the source of CO₂-rich fluid in the lower crust is generally attributed to the underplating of mafic to ultramafic melt (Condie et al., 1982). However, it is unclear if CO₂-flux is contemporaneous or post peak metamorphic event (Fitzsimons et al., 2018).

The presence of CO₂ and CH₄ rich inclusion in felsic volcanics containing ore deposits in the northern part of the craton also indicate decarbonation occurred during the prograde path (Saravanan & Mishra, 2009). Unfortunately, constraining origin of carbon-rich phases and their behaviour in a thermodynamically constrained P-T space is currently limited and this is therefore beyond the scope of this study. Further work on the issue of multiple fluid phase systems would be required.

Conclusion

The approach presented in this contribution shows that crustal differentiation processes and water flux, at the scale of the crustal column, can be quantified with thermodynamic modelling. This study highlights the importance of crustal scale compositional heterogeneity as a major control on the nature of partial melting reactions, the composition of the resulting magmas (melt + peritectic phases) and the rheology of the crust.

As with many other Archean terrains (Condie, 1981), the crustal column in the Dharwar craton is composed of a ~ 15 km thick supracrustal sequence overlying a ~ 20 km thick felsic basement, the Peninsular gneisses (Fig. 11a). At depth, with no addition of water from any external source, the volume of melt in the basement does not exceed 5 vol.%, for an apparent geotherm of 60 °C.kbar⁻¹ (Fig. 11a).

The composition of the supracrustal unit is critical as it influences the maximum amount of water retained in the rock as well as the chemistry and volume of the produced phases. In the case of the Dharwar, the burial of supracrustal rocks containing ~ 1.6 wt.% of water, at a speed of ~ 1.9 km.Ma⁻¹, release a maximum of 50 % of its mineral-bound water into the surrounding basement, triggering water-present partial melting (Fig. 9b). The modelling presented here shows that the quantity of water lost from the buried supracrustal package is enough to produce the range of syn- to post-intrusion chemistry and volume observed in the Dharwar craton. No additional degassing from the underlying mantle would have been required. It is difficult to assess how far the water might transfer from the buried supracrustal packages to the surrounding basement. However, it is likely that most of the water-fluxed partial melting happened within the vicinity of the contact between the Peninsular gneisses and the supracrustal unit, where $0.27 < \text{SU/B} < 1.5$. Consequently, syn- to post-tectonic anatectic intrusions produced by water-fluxed melting are likely to be concentrated on the edge of the felsic domes, in a magmatic channel, at depths ranging from 10-12 kbars to 4 kbars (Fig. 11b). Anatectic granites resulting from biotite-breakdown water-absent partial melting are located further away from the keel/dome contact and at depth ranging from 3 to 7 kbars. This is consistent with granitoids occurring along the mapped greenstone schist belt (Chardon et al, 2002, Jayananda et al., 2018). Such pattern is also visible in the Pilbara craton (Collins et al., 1998)

These findings demonstrate not only the complexity of crustal differentiation, but also that it is possible to quantify the processes responsible for the stabilization of continental margins at the Archean-Proterozoic boundary. This period of crustal maturation at *ca.* 2.5 Ga, via the burial and intense reworking of a large amount supracrustal material eventually, is argued to drive the stabilisation of the continental crust (Dyck et al., 2015; Nicoli et al, 2016, Nicoli & Dyck, 2018). Vezinet et al. (2017) argued that the amount of mineral-bound water in the Archean basement of the Kaapvaal craton is not enough to generate large volume of anatectic melt below 1000 °C. Hence, it is likely that the increase of granitoid diversity in the late Archean (Moyen et al., 2003) might coincide with crustal mechanisms progressively shifting from a bimodal “closed” system (juvenile magma + felsic basement) in the Archean

towards a three-endmembers “open” system where surface inputs are permitted via the efficient burial of weathered crustal material in the Phanerozoic.

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References

- Bhadra, S., Gupta, S., & Banerjee, M. (2004). Structural evolution across the Eastern Ghats Mobile Belt–Bastar craton boundary, India: hot over cold thrusting in an ancient collision zone. *Journal of Structural Geology*, 26(2), 233-245.
- Bhattacharya, S., Panigrahi, M. K., Sachan, H. K., & Kharya, A. (2014). Oxygen isotope ratio of quartz veins from the auriferous Ramagiri–Penakacherla schist belt and surrounding granitoids in the Eastern Dharwar craton: A case for a possible link between gold mineralization and granite magmatism. *Ore Geology Reviews*, 63, 201-208.
- Bouhallier, H., Chardon, D., & Choukroune, P. (1995). Strain patterns in Archaean dome-and-basin structures: The Dharwar craton (Karnataka, South India). *Earth and Planetary Science Letters*, 135(1-4), 57-75.
- Bouhallier, H., Choukroune, P., & Ballèvre, M. (1993). Diapirism, bulk homogeneous shortening and transcurrent shearing in the Archaean Dharwar craton: the Holenarsipur area, southern India. *Precambrian Research*, 63(1-2), 43-58.
- Brown, M. (2013). Granite: From genesis to emplacement. *GSA Bulletin*, 125(7-8), 1079-1113.
- Chadwick, B., Vasudev, V. N., & Hegde, G. V. (2000). The Dharwar craton, southern India, interpreted as the result of Late Archaean oblique convergence. *Precambrian Research*, 99(1-2), 91-111.
- Chadwick, B., Vasudev, V. N., Hegde, G. V., & Nutman, A. P. (2007). Structure and SHRIMP U/Pb zircon ages of granites adjacent to the Chitradurga schist belt: Implications for Neoarchaean convergence in the Dharwar craton, southern India. *Journal of the Geological Society of India*, 69(1), 5-24.
- Chardon, D., Choukroune, P., & Jayananda, M. (1996). Strain patterns, décollement and incipient sagducted greenstone terrains in the Archaean Dharwar craton (south India).

Journal of Structural Geology, 18(8), 991-1004.

Chardon, D., Choukroune, P., & Jayananda, M. (1998). Sinking of the Dharwar basin (South India): implications for Archaean tectonics. *Precambrian Research*, 91(1-2), 15-39.

Chardon, D., Gapais, D., & Cagnard, F. (2009). Flow of ultra-hot orogens: a view from the Precambrian, clues for the Phanerozoic. *Tectonophysics*, 477(3-4), 105-118.

Chardon, D., & Jayananda, M. (2008). Three-dimensional field perspective on deformation, flow, and growth of the lower continental crust (Dharwar craton, India). *Tectonics*, 27(1).

Chardon, D., Jayananda, M., & Peucat, J. J. (2011). Lateral constrictional flow of hot orogenic crust: Insights from the Neoproterozoic of south India, geological and geophysical implications for orogenic plateaux. *Geochemistry, Geophysics, Geosystems*, 12(2).

Clemens, J. D. (2006). *Melting of the continental crust: fluid regimes, melting reactions, and source-rock fertility* (pp. 297-331). Cambridge University Press.

Clemens, J. D., Buick, I. S., & Stevens, G. (2016). Fluids, melting, granulites and granites: A controversy-reply to the commentary of. *Precambrian Research*, 278, 400-404.

Clemens, J. D., & Petford, N. (1999). Granitic melt viscosity and silicic magma dynamics in contrasting tectonic settings. *Journal of the Geological Society*, 156(6), 1057-1060.

Clemens, J. D., & Stevens, G. (2012). What controls chemical variation in granitic magmas?. *Lithos*, 134, 317-329.

Clemens, J. D., & Vielzeuf, D. (1987). Constraints on melting and magma production in the crust. *Earth and Planetary Science Letters*, 86(2-4), 287-306.

Collins, W. (1993). Melting of Archaean sialic crust under high aH₂O conditions: genesis of 3300 Ma Na-rich granitoids in the Mount Edgar Batholith, Pilbara Block, Western Australia. *Precambrian Research*, 60(1-4), 151-174.

Collins, A. S., Santosh, M., Braun, I., & Clark, C. (2007). Age and sedimentary provenance of the Southern Granulites, South India: U-Th-Pb SHRIMP secondary ion mass spectrometry. *Precambrian Research*, 155(1-2), 125-138.

Collins, W. J., Van Kranendonk, A. M., & Teyssier, C. (1998). Partial convective overturn of Archaean crust in the east Pilbara Craton, Western Australia: driving mechanisms and tectonic implications. *Journal of Structural Geology*, 20(9-10), 1405-1424.

Condie, K. C. (1981). *Archean greenstone belts* (Vol. 3). Elsevier.

Condie, K. C. (1993). Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. *Chemical geology*, 104(1-4), 1-37.

Condie, K. C., Allen, P., & Narayana, B. L. (1982). Geochemistry of the Archean low-to high-grade transition zone, southern India. *Contributions to Mineralogy and Petrology*, 81(3), 157-167.

Connolly, J. A. D. (2009). The geodynamic equation of state: what and how. *Geochemistry, Geophysics, Geosystems*, 10(10).

Connolly, J. A. D. (1997). Devolatilisation-generated fluid pressure and deformation-propagated fluid flow during prograde regional metamorphism. *Journal of Geophysical Research: Solid Earth*, 102(B8), 18149-18173.

Diener, J. F. A., & Powell, R. (2012). Revised activity–composition models for clinopyroxene and amphibole. *Journal of Metamorphic Geology*, 30(2), 131-142.

Drury, S. A., Harris, N. B. W., Holt, R. W., Reeves-Smith, G. J., & Wightman, R. T. (1984). Precambrian tectonics and crustal evolution in South India. *The Journal of Geology*, 92(1), 3-20.

Dyck, B., Reno, B. L., & Kokfelt, T. F. (2015). The Majorqaaq Belt: a record of Neoarchean orogenesis during final assembly of the North Atlantic Craton, southern West Greenland. *Lithos*, 220, 253-271.

Etheridge, M. A., Wall, V. J., & Vernon, R. H. (1983). The role of the fluid phase during regional metamorphism and deformation. *Journal of Metamorphic Geology*, 1(3), 205-226.

Ferry, J. T., & Spear, F. S. (1978). Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contributions to mineralogy and petrology*, 66(2), 113-117.

Fitzsimons, I.C.W., Clark, C., Chilekwa, M. & Santosh, M. (2018) The dark history of charnockite. 2018 Granulites & Granulites Meeting, Ullapool, Scotland.

Friend, C. R. L., & Nutman, A. P. (1991). SHRIMP U-Pb geochronology of the Closepet granite and Peninsular gneiss, Karnataka, South India. *Journal of the Geological Society of India*, 38(4), 357-368.

Friend, C. R. L., & Nutman, A. P. (1992). Response of zircon U–Pb isotopes and whole-rock geochemistry to CO₂ fluid-induced granulite-facies metamorphism, Kabbaldurga, Karnataka, South India. *Contributions to Mineralogy and Petrology*, 111(3), 299-310.

Frost, B. R., & Frost, C. D. (1987). CO₂, melts and granulite metamorphism. *Nature*, 327(6122), 503.

- Garcia-Arias, M., & Stevens, G. (2017). Phase equilibrium modelling of granite magma petrogenesis: A. An evaluation of the magma compositions produced by crystal entrainment in the source. *Lithos*, 277, 131-153.
- Gardner, J. E., Rutherford, M., Carey, S., & Sigurdsson, H. (1995). Experimental constraints on pre-eruptive water contents and changing magma storage prior to explosive eruptions of Mount St Helens volcano. *Bulletin of Volcanology*, 57(1), 1-17.
- Gopalakrishna, D., Hansen, E. C., Janardhan, A. S., & Newton, R. C. (1986). The southern high-grade margin of the Dharwar Craton. *The Journal of Geology*, 94(2), 247-260.
- Green, E. C. R., White, R. W., Diener, J. F. A., Powell, R., Holland, T. J. B., & Palin, R. M. (2016). Activity–composition relations for the calculation of partial melting equilibria in metabasic rocks. *Journal of Metamorphic Geology*, 34(9), 845-869.
- Guevara, V. E., & Caddick, M. J. (2016). Shooting at a moving target: phase equilibria modelling of high-temperature metamorphism. *Journal of Metamorphic Geology*, 34(3), 209-235.
- Hansen, E. C., Janardhan, A. S., Newton, R. C., Prame, W. K. B. N., & Kumar, G. R. (1987). Arrested charnockite formation in southern India and Sri Lanka. *Contributions to Mineralogy and Petrology*, 96(2), 225-244.
- Hansen, E. C., Newton, R. C., & Janardhan, A. S. (1984). Fluid inclusions in rocks from the amphibolite-facies gneiss to charnockite progression in southern Karnataka, India: direct evidence concerning the fluids of granulite metamorphism. *Journal of Metamorphic Geology*, 2(3), 249-264.
- Hansen, E. C., Newton, R. C., Janardhan, A. S., & Lindenberg, S. (1995). Differentiation of late Archean crust in the eastern Dharwar craton, Krishnagiri-Salem area, south India. *The Journal of Geology*, 103(6), 629-651.
- Hokada, T., Horie, K., Satish-Kumar, M., Ueno, Y., Nasheeth, A., Mishima, K., & Shiraishi, K. (2013). An appraisal of Archaean supracrustal sequences in Chitradurga schist belt, western Dharwar Craton, southern India. *Precambrian Research*, 227, 99-119.
- Holdaway, M. J., & Lee, S. M. (1977). Fe-Mg cordierite stability in high-grade pelitic rocks based on experimental, theoretical, and natural observations. *Contributions to Mineralogy and Petrology*, 63(2), 175-198.
- Holland, T., & Powell, R. (1996). Thermodynamics of order-disorder in minerals: II. Symmetric formalism applied to solid solutions. *American Mineralogist*, 81(11-12), 1425-1437.
- Holland, T. J. B., & Powell, R. T. J. B. (1998). An internally consistent thermodynamic data set for phases of petrological interest. *Journal of metamorphic Geology*, 16(3), 309-343.

- Holland, T., & Powell, R. (2003). Activity–composition relations for phases in petrological calculations: an asymmetric multicomponent formulation. *Contributions to Mineralogy and Petrology*, 145(4), 492-501.
- Holland, T. J. B., & Powell, R. (2011). An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *Journal of Metamorphic Geology*, 29(3), 333-383.
- Holtz, F., & Johannes, W. (1994). Maximum and minimum water contents of granitic melts: implications for chemical and physical properties of ascending magmas. *Lithos*, 32(1-2), 149-159.
- Janardhan, A. S., Newton, R. C., & Hansen, E. C. (1982). The transformation of amphibolite facies gneiss to charnockite in southern Karnataka and northern Tamil Nadu, India. *Contributions to Mineralogy and Petrology*, 79(2), 130-149.
- Jayananda, M., Chardon, D., Peucat, J. J., & Capdevila, R. (2006). 2.61 Ga potassic granites and crustal reworking in the western Dharwar craton, southern India: tectonic, geochronologic and geochemical constraints. *Precambrian Research*, 150(1-2), 1-26.
- Jayananda, M., Moyen, J. F., Martin, H., Peucat, J. J., Auvray, B., & Mahabaleswar, B. (2000). Late Archaean (2550–2520 Ma) juvenile magmatism in the Eastern Dharwar craton, southern India: constraints from geochronology, Nd–Sr isotopes and whole rock geochemistry. *Precambrian Research*, 99(3-4), 225-254.
- Jayananda, M., Santosh, M., & Aadhiseshan, K. R. (2018). Formation of Archean (3600–2500 Ma) continental crust in the Dharwar Craton, southern India. *Earth-Science Reviews*.
- Jia, Y., & Kerrich, R. (2000). Giant quartz vein systems in accretionary orogenic belts: the evidence for a metamorphic fluid origin from $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ studies. *Earth and Planetary Science Letters*, 184(1), 211-224.
- Kretz, R. (1983). Symbols for rock-forming minerals. *American mineralogist*, 68(1-2), 277-279.
- Le Breton, N., & Thompson, A. B. (1988). Fluid-absent (dehydration) melting of biotite in metapelites in the early stages of crustal anatexis. *Contributions to Mineralogy and Petrology*, 99(2), 226-237.
- Lee, Y., & Cho, M. (2013). Fluid-present disequilibrium melting in Neoproterozoic arc-related migmatites of Daeijak Island, western Gyeonggi Massif, Korea. *Lithos*, 179, 249-262.
- Maaløe, S., & Wyllie, P. J. (1975). Water content of a granite magma deduced from the sequence of crystallization determined experimentally with water-undersaturated conditions. *Contributions to Mineralogy and Petrology*, 52(3), 175-191.

- Mahabaleshwar, B., Jayananda, M., Peucat, J. J., & Shadakshara Swamy, N. (1995). Archean high-grade gneiss complexes from southern Malagun-Sivasamudram areas, Karnataka, southern India; Petrogenesis and crustal evolution. *Jour. Geol. Soc. India*, 45, 33-49.
- Mogk, D. W. (1992). Ductile shearing and migmatization at mid-crustal levels in an Archean high-grade gneiss belt, northern Gallatin Range, Montana, USA. *Journal of Metamorphic Geology*, 10(3), 427-438.
- Morizet, Y., Nichols, A. R., Kohn, S. C., Brooker, R. A., & Dingwell, D. B. (2007). The influence of H₂O and CO₂ on the glass transition temperature: insights into the effects of volatiles on magma viscosity. *European Journal of Mineralogy*, 19(5), 657-669.
- Moyen, J. F. (2000). *Le magmatisme granitique a la transition archeen-proterozoique: l'exemple du craton de dharwar, inde du sud (granite de closepet et intrusions associees)* (Doctoral dissertation, Clermont-Ferrand 2).
- Moyen, J. F., Martin, H., Jayananda, M., & Auvray, B. (2003). Late Archean granites: a typology based on the Dharwar Craton (India). *Precambrian Research*, 127(1-3), 103-123.
- Moyen, J. F., Martin, H., & Jayananda, M. (2001). Multi-element geochemical modelling of crust–mantle interactions during late-Archean crustal growth: the Closepet granite (South India). *Precambrian Research*, 112(1-2), 87-105.
- Naqvi, S. M., & Hussain, S. M. (1972). Petrochemistry of early Precambrian metasediments from the central part of the Chitaldrug schist belt, Mysore, India. *Chemical Geology*, 10(2), 109-135.
- Naqvi, S. M., Sawkar, R. H., Rao, D. S., Govil, P. K., & Rao, T. G. (1988). Geology, geochemistry and tectonic setting of Archean greywackes from Karnataka Nucleus, India. *Precambrian research*, 39(3), 193-216.
- Naha, K., Srivivasan, R., & Jayaram, S. (1993). Structural relations of charnockites of the Archean Dharwar craton, southern India. *Journal of Metamorphic Geology*, 11(6), 889-895.
- Perkins III, D., & Newton, R. C. (1981). Charnockite geobarometers based on coexisting garnet—pyroxene—plagioclase—quartz. *Nature*, 292(5819), 144.
- Nédélec, A., Minyem, D., & Barbey, P. (1993). High-P—high-T anatexis of Archean tonalitic grey gneisses: the Eseka migmatites, Cameroon. *Precambrian Research*, 62(3), 191-205.
- Nicoli, G., & Dyck, B. (2018). Exploring the metamorphic consequences of secular change in the siliciclastic compositions of continental margins. *Geoscience Frontiers*.
- Nicoli, G., Moyen, J. F., & Stevens, G. (2016). Diversity of burial rates in convergent settings decreased as Earth aged. *Scientific reports*, 6, 26359.

- Nicoli, G., Stevens, G., Moyen, J. F., Vezinet, A., & Mayne, M. (2017). Insights into the complexity of crustal differentiation: K₂O-poor leucosomes within metasedimentary migmatites from the Southern Marginal Zone of the Limpopo Belt, South Africa. *Journal of Metamorphic Geology*.
- Papale, P., Neri, A., & Macedonio, G. (1998). The role of magma composition and water content in explosive eruptions: 1. Conduit ascent dynamics. *Journal of Volcanology and Geothermal Research*, 87(1-4), 75-93.
- Palin, R. M., Weller, O. M., Waters, D. J., & Dyck, B. (2016a). Quantifying geological uncertainty in metamorphic phase equilibria modelling; a Monte Carlo assessment and implications for tectonic interpretations. *Geoscience Frontiers*, 7(4), 591-607.
- Palin, R. M., & White, R. W. (2016b). Emergence of blueschists on Earth linked to secular changes in oceanic crust composition. *Nature Geoscience*, 9(1), 60.
- Percival, J. A. (1991). Granulite-Facies Metamorphism and Crustal Magmatism in the Ashuanipi Complex, Quebec—Labrador, Canada. *Journal of Petrology*, 32(6), 1261-1297.
- Patino Douce, A. E., & Beard, J. S. (1996). Effects of P, f (O₂) and Mg/Fe ratio on dehydration melting of model metagreywackes. *Journal of Petrology*, 37(5), 999–1024.
- Petford, N., Cruden, A. R., McCaffrey, K. J. W., & Vigneresse, J. L. (2000). Granite magma formation, transport and emplacement in the Earth's crust. *Nature*, 408(6813), 669.
- Peucat, J. J., Jayananda, M., Chardon, D., Capdevila, R., Fanning, C. M., & Paquette, J. L. (2013). The lower crust of the Dharwar Craton, Southern India: Patchwork of Archean granulitic domains. *Precambrian Research*, 227, 4-28.
- Phillips, G. N., & Powell, R. (1993). Link between gold provinces. *Economic Geology*, 88(5), 1084-1098.
- Phillips, G. N., & Powell, R. (2010). Formation of gold deposits: a metamorphic devolatilization model. *Journal of Metamorphic Geology*, 28(6), 689-718.
- Pichamuthu, C. S., Srinivasan, R., & Bhasker, A. A. (1981). Archaean crustal thickness of greenstone granite belts of South India. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences*, 90(3), 217-226.
- Pickering, J. M., & Johnston, D. A. (1998). Fluid-absent melting behaviour of a two-mica metapelite: Experimental constraints on the origin of Black Hills granite. *Journal of Petrology*, 39(10), 1787–1804.
- Pili, E., Kennedy, B. M., Conrad, M. E., & Gratier, J. P. (2011). Isotopic evidence for the infiltration of mantle and metamorphic CO₂–H₂O fluids from below in faulted rocks from the San Andreas Fault system. *Chemical Geology*, 281(3-4), 242-252.

- Piper, J. D. A., Mallik, S. B., Bandyopadhyay, G., Mondal, S., & Das, A. K. (2003). Palaeomagnetic and rock magnetic study of a deeply exposed continental section in the Charnockite Belt of southern India: implications to crustal magnetisation and palaeoproterozoic continental nuclei. *Precambrian Research*, 121(3-4), 185-219.
- Raase, P., Raith, M., Ackermann, D., & Lal, R. K. (1986). Progressive metamorphism of mafic rocks from greenschist to granulite facies in the Dharwar Craton of South India. *The Journal of Geology*, 94(2), 261-282.
- Reichardt, H., & Weinberg, R. F. (2012). Hornblende chemistry in meta- and diatexites and its retention in the source of leucogranites: an example from the Karakoram Shear Zone, NW India. *Journal of Petrology*, 53(6), 1287-1318.
- Robert, F., Boullier, A. M., & Firdaus, K. (1995). Gold-quartz veins in metamorphic terranes and their bearing on the role of fluids in faulting. *Journal of Geophysical Research: Solid Earth*, 100(B7), 12861-12879.
- Rollinson, H. R., Windley, B. F., & Ramakrishnan, M. (1981). Contrasting high and intermediate pressures of metamorphism in the Archaean Sargur Schists of southern India. *Contributions to Mineralogy and Petrology*, 76(4), 420-429.
- Rosenberg, C. L., & Handy, M. R. (2005). Experimental deformation of partially melted granite revisited: implications for the continental crust. *Journal of metamorphic Geology*, 23(1), 19-28.
- Sarangi, S., Sarkar, A., Srinivasan, R., & Patel, S. C. (2012). Carbon isotope studies of auriferous quartz carbonate veins from two orogenic gold deposits from the Neoarchean Chitradurga schist belt, Dharwar craton, India: evidence for mantle/magmatic source of auriferous fluid. *Journal of Asian Earth Sciences*, 52, 1-11.
- Saravanan, C. S., & Mishra, B. (2009). Uniformity in sulfur isotope composition in the orogenic gold deposits from the Dharwar Craton, southern India. *Mineralium Deposita*, 44(5), 597-605.
- Sarma, D. S., Fletcher, I. R., Rasmussen, B., McNaughton, N. J., Mohan, M. R., & Groves, D. I. (2011). Archaean gold mineralization synchronous with late cratonization of the Western Dharwar Craton, India: 2.52 Ga U-Pb ages of hydrothermal monazite and xenotime in gold deposits. *Mineralium Deposita*, 46(3), 273-288.
- Sarma, D. S., McNaughton, N. J., Belusova, E., Mohan, M. R., & Fletcher, I. R. (2012). Detrital zircon U-Pb ages and Hf-isotope systematics from the Gadag Greenstone Belt: Archean crustal growth in the western Dharwar Craton, India. *Gondwana Research*, 22(3-4), 843-854.

- Sarma, D. S., Mcnaughton, N. J., Fletcher, I. R., Groves, D. I., Mohan, M. R., & Balaram, V. (2008). Timing of gold mineralization in the Hutti gold deposit, Dharwar Craton, South India. *Economic Geology*, 103(8), 1715-1727.
- Sawyer, E. W., Cesare, B., & Brown, M. (2011). When the continental crust melts. *Elements*, 7(4), 229-234.
- Smye, A. J., Jackson, C. R., Konrad-Schmolke, M., Hesse, M. A., Parman, S. W., Shuster, D. L., & Ballentine, C. J. (2017). Noble gases recycled into the mantle through cold subduction zones. *Earth and Planetary Science Letters*, 471, 65-73.
- Stähle, H. J., Raith, M., Hoernes, S., & Delfs, A. (1987). Element mobility during incipient granulite formation at Kabbaldurga, southern India. *Journal of Petrology*, 28(5), 803-834.
- Stevens, G., & Clemens, J. D. (1993). Fluid-absent melting and the roles of fluids in the lithosphere: a slanted summary?. *Chemical Geology*, 108(1-4), 1-17.
- Stevens, G., Villaros, A., & Moyen, J. F. (2007). Selective peritectic garnet entrainment as the origin of geochemical diversity in S-type granites. *Geology*, 35(1), 9-12.
- Sundaram, R. M., Surendranath, M., & Reddy, U. S. N. (2007, January). Revised Gravity Maps of India (2006 series)—A Cartographic Perspective. In *Conference Proceedings of Map World Forum, January 22e25*.
- Swami Nath, J., Ramakrishnan, M., & Viswanatha, M. N. (1976). Dharwar stratigraphic model and Karnataka craton evolution. *Rec. Geol. Surv. India*, 107(2), 149-175.
- Taylor, P. N., Chadwick, B., Moorbath, S., Ramakrishnan, M., & Viswanatha, M. N. (1984). Petrography, chemistry and isotopic ages of Peninsular gneiss, Dharwar acid volcanic rocks and the Chitradurga granite with special reference to the late Archean evolution of the Karnataka craton, Southern India. *Precambrian Research*, 23(3-4), 349-375.
- Taylor, S. R., & McLennan, S. M. (1995). The geochemical evolution of the continental crust. *Reviews of Geophysics*, 33(2), 241-265.
- Taylor, J., Nicoli, G., Stevens, G., Frei, D., & Moyen, J. F. (2014). The processes that control leucosome compositions in metasedimentary granulites: perspectives from the Southern Marginal Zone migmatites, Limpopo Belt, South Africa. *Journal of Metamorphic Geology*, 32(7), 713-742.
- Thompson, A. B. (1982). Dehydration melting of pelitic rocks and the generation of H₂O-undersaturated granitic liquids. *American Journal of Science*, 282(10), 1567-1595.
- Touret, J., Grégoire, M., & Teitchou, M. (2010). Was the lethal eruption of Lake Nyos related to a double CO₂/H₂O density inversion?. *Comptes Rendus Geoscience*, 342(1), 19-26.

- Vezinet, A., Moyen, J. F., Stevens, G., Nicoli, G., Laurent, O., Couzinié, S., & Frei, D. (2018). A record of 0.5 Ga of evolution of the continental crust along the northern edge of the Kaapvaal Craton, South Africa: Consequences for the understanding of Archean geodynamic processes. *Precambrian Research*, 305, 310-326.
- Vielzeuf, D., Clemens, J. D., Pin, C., & Moinet, E. (1990). Granites, granulites, and crustal differentiation. In *Granulites and crustal evolution* (pp. 59-85). Springer, Dordrecht.
- Villaros, A., Stevens, G., Moyen, J. F., & Buick, I. S. (2009). The trace element compositions of S-type granites: evidence for disequilibrium melting and accessory phase entrainment in the source. *Contributions to Mineralogy and Petrology*, 158(4), 543-561.
- Wade, J., Dyck, B., Palin, R. M., Moore, J. D., & Smye, A. J. (2017). The divergent fates of primitive hydrospheric water on Earth and Mars. *Nature*, 552(7685), 391.
- Ward, R., Stevens, G., & Kisters, A. (2008). Fluid and deformation induced partial melting and melt volumes in low-temperature granulite-facies metasediments, Damara Belt, Namibia. *Lithos*, 105(3-4), 253-271.
- Waters, D. J. (1988). Partial melting and the formation of granulite facies assemblages in Namaqualand, South Africa. *Journal of Metamorphic Geology*, 6(4), 387-404.
- Watt, G. R., & Harley, S. L. (1993). Accessory phase controls on the geochemistry of crustal melts and restites produced during water-undersaturated partial melting. *Contributions to Mineralogy and Petrology*, 114(4), 550-566.
- Weinberg, R. F., & Hasalová, P. (2015). Water-fluxed melting of the continental crust: A review. *Lithos*, 212, 158-188.
- White, R. W., & Powell, R. (2002). Melt loss and the preservation of granulite facies mineral assemblages. *Journal of Metamorphic Geology*, 20(7), 621-632.
- White, R. W., & Powell, R. (2010). Retrograde melt–residue interaction and the formation of near-anhydrous leucosomes in migmatites. *Journal of Metamorphic Geology*, 28(6), 579-597.
- White, R. W., Powell, R., Holland, T. J. B., Johnson, T. E., & Green, E. C. R. (2014). New mineral activity–composition relations for thermodynamic calculations in metapelitic systems. *Journal of Metamorphic Geology*, 32(3), 261-286.
- White, R. W., Powell, R., Holland, T. J. B., & Worley, B. A. (2000). The effect of TiO₂ and Fe₂O₃ on metapelitic assemblages at greenschist and amphibolite facies conditions: mineral equilibria calculations in the system K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O-TiO₂-Fe₂O₃. *Journal of Metamorphic Geology*, 18(5), 497-511.
- Yakymchuk, C., & Brown, M. (2014). Consequences of open-system melting in tectonics. *Journal of the Geological Society*, 171(1), 21-40.

Caption

Figure 1 - Geological map and metamorphic conditions (after Moyen, 2000). (a) Simplified geological map of the Dharwar craton (after the Geological survey of India, Sundaram 2007; Chardon et al, 2008). Cities: Mangalore (Ma), Bangalore (B), Mysore (My). WDC: Western Dharwar craton; EDC: Eastern Dharwar craton. Schist belts: Dharwar (DB), Sandur (SB), Chitradurga (CB), Kolar (KB); Dashed lines: metamorphic grade isogrades, green schist facies conditions (gs); amphibolite facies conditions (amph); granulite facies conditions (gr). A-A' and B-B': N-S crustal transects shown in c; (b) P-T conditions along the A-A' and B-B' transects (see text for references). The average P-T path (thick dashed line) indicates an evolution from 450°C and 2.2 kbar to 900°C and 10 kbar. The average apparent geotherm is 60 °C.kbar⁻¹.

Figure 2 - Evolution of the Dharwar craton from the Neoproterozoic to the early Proterozoic (adapted after Moyen, 2000). SZ: shear zone. At ca. 2.5 Ga, gravitational instabilities caused a vertical reorganization of the WDC with sinking of the supracrustal lithologies and ascent of a partially molten middle and lower crust, resulting in a dome and keel structure.

Figure 3 - Bulk water content in water-bearing minerals at subsolidus conditions. Water content in the supracrustal lithologies (a) Andesite; (b) Basalt; (c) Felsic volcanics; (d) Greywacke; (e) Water content of the supracrustal unit, calculated using proportions from Condie (1993); (f) Water content in the basement. + : phase stable at higher temperature, - : phase exhaustion. Abbreviations after Kretz, 1983

Figure 4 - Bulk mineral-bound water budget water content along the prograde path (60 °C.kbar⁻¹) (a) The supracrustal unit (SU): 27.5% felsic volcanic (FV), 25% basalt (B), 12.5% andesite (A), 35% greywacke (G) (Condie, 1993). Loss of water in the supracrustal unit is mainly caused by the exhaustion of chlorite and epidote (b) Supracrustal unit/Basement volumetric ratio (SU/B) curves show the amount of water loss (wt%) from the SU between 450 °C and the solidus. The basement curve shows maximum mineral-bound water content along the prograde path.

Figure 5 - Anatexis melt. (a) Volume of the different phases in the basement from subsolidus to peak metamorphic conditions (900 °C – 10 kbar); (b) Chemistry of the modelled anatexis melt from the supracrustal unit and the basement (in mol). Dashed line – 1: water-present solidus; 2: water-saturated solidus.

Figure 6 - Difference in density ($\Delta\rho_1 = \rho_{\text{Supracrustal Unit}}/\rho_{\text{Basement}}$) between the supracrustal unit and the basement calculated for maximum mineral-bound water values.

Figure 7 - Gold deposits in the greenstone belts in the northern part of the craton. 1: Chardon et al. (2002); 2 : Sarma et al. (2008); 3 : Sarma et al.,(2011); 4 : Sarma et al., (2012); 5:

Bhattacharya et al. (2014); 6 : Peucat et al. (2013). Closepet (Friend & Nutman, 1991), Syn- to post-tectonic intrusions (Jayananda et al., 2018)

Figure 8 – Density contrast in the basement ($\Delta\rho_2 = \rho_{\text{Basement water-absent}}/\rho_{\text{Basement water-fluxed}}$) above solidus conditions, between rocks that experienced water-fluxed melting and dryer parts of the felsic crust.

Figure 9 – Comparison of the compositions of the syn to post-tectonic anatectic granites in the Eastern Dharwar craton (EDC) and Western Dharwar craton (WDC) with the modelled melt compositions (in mole) . The starts indicate the average modelled melt compositions. The arrows indicates the influence of the presence of peritectic and magmatic phases on the magma composition (Pl, Grt, Opx) ($A/NK = Al/[Na+K]$ molar ratio).

Figure 10 – P-T estimates for the syn- to post-tectonic anatectic granites in the Eastern Dharwar craton (EDC) and Western Dharwar craton (WDC). (a) Magma produced by biotite breakdown water-absent partial melting; (b) Magma produced by water-fluxed partial melting. The background show the volume of the melt phase. Side boxes: frequency distribution of P-T conditions (number of analyses $n_{\text{EDC}} = 45$; $n_{\text{WDC}} = 127$).

Figure 11 - Water budget and formation of syn- to post-tectonic intrusions in the Dharwar craton. (a) Prior to the burial of the supracrustal unit. Temperature and melt volume isogrades have been calculated for an apparent geotherm of $60\text{ }^{\circ}\text{C.kbar}^{-1}$. (b) Devolatilisation of epidote (Ep) and chlorite (Chl) during the rapid burial of water-saturated supracrustal lithologies. During devolatilisation, some of the water ascents towards the surface forming ore deposits. Partial melting of the surrounding basement happens under free water-present and free water absent conditions in a magma channel along the supracrustal keel and felsic dome contact. Most of the magma from the basement form between 2 kbars and 7 kbars. Magma formed by water-fluxed partial melting also crystallise at greater depth ($> 10\text{ kbar}$).

Table 1 - Bulk composition of the starting material (wt%). SU: supracrustal unit; B: Basement (after Condie, 1993; Taylor et al., 1984). Fe_2O_3 was estimated from the volume of reduced iron, $\text{Fe}_2\text{O}_3 = 1.11135*\text{FeO}$

	Felsic Volcanic	Basalt	Andesite	Greywacke	SU	Potassic granite	TTG	B
Vol (%)	27.5	25	12.5	35		30	70	
SiO ₂	73.00	50.80	59.10	65.40	61.74	73.18	72.99	73.05
TiO ₂	0.35	1.42	0.76	0.74	0.79	0.22	0.21	0.21
Al ₂ O ₃	13.90	15.30	16.30	15.50	14.80	13.28	14.70	14.27
Fe ₂ O ₃	0.33	0.73	0.57	0.56	0.53	0.18	0.22	0.21
FeO	2.51	8.84	5.89	5.60	5.50	1.66	1.97	1.87
MgO	0.74	6.90	3.90	2.20	3.14	0.36	0.49	0.45
CaO	1.40	9.60	6.20	2.50	4.37	1.41	2.19	1.96
Na ₂ O	3.30	2.70	3.80	3.00	3.04	3.78	5.24	4.80
K ₂ O	3.70	0.76	1.20	2.40	2.15	3.93	1.61	2.30
Total	99.22	97.05	97.72	97.90	96.06	98.00	99.59	99.11
Mg#	0.16	0.34	0.31	0.21	0.28	0.11	0.13	0.13
A/CNK	1.28	1.08	1.22	1.56	1.29	1.11	1.17	1.15





















